CMIP3 Subtropical Stratocumulus Feedback Interpreted Through a Mixed-Layer Model

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Motivation

- Subtropical low cloud feedbacks are a primary source of climate change uncertainty (IPCC AR4)
- Previous studies (Bony et al, Clim Dyn 2004, Medeiros et al, J. Clim. 2008) suggest that low cloud problems in GCMs stem from cloud parameterizations rather than large-scale circulation

Idea: Can a limited-area model forced by CMIP3 large-scale forcings reduce inter-model spread and improve understanding of low cloud feedback, thereby reducing climate-change uncertainty?

Methodology

Large-scale conditions from all available CMIP3 GCMs are used as boundary conditions for an atmospheric mixed-layer model (MLM) extended to predict cloud fraction (see Fig 1).

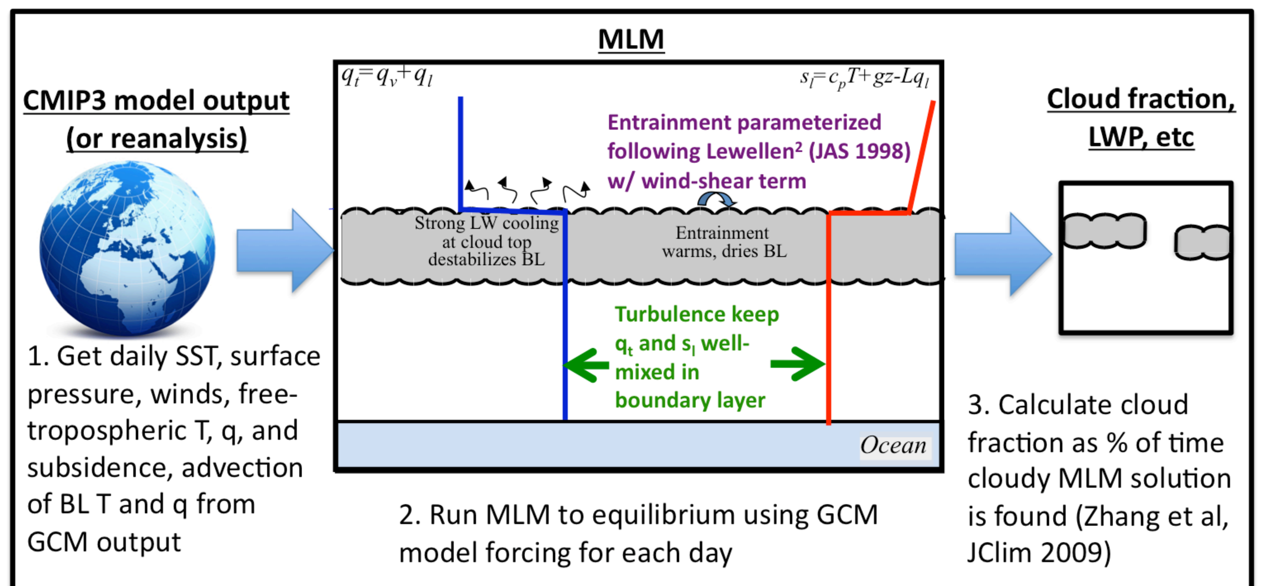

Fig. 1: Diagram of 3-step modeling approach.

Why a MLM?

- Efficient (can do climate-length runs with many GCMs)
- Physically-based
- Easy to interpret

Simulations Used:

20C3M years 1980-2000 & scenario A1B years 2080-2100

GCM→MLM coupling details:

- Using BL depth estimation to ensure upper boundary data is in free troposphere
- Computing subsidence assuming constant divergence (using 10m winds)
- Predicting T and q gradients from ∇SST and ∇q_s(SST); assuming $v \bullet \nabla z_i$=0.49mm/day

Validation

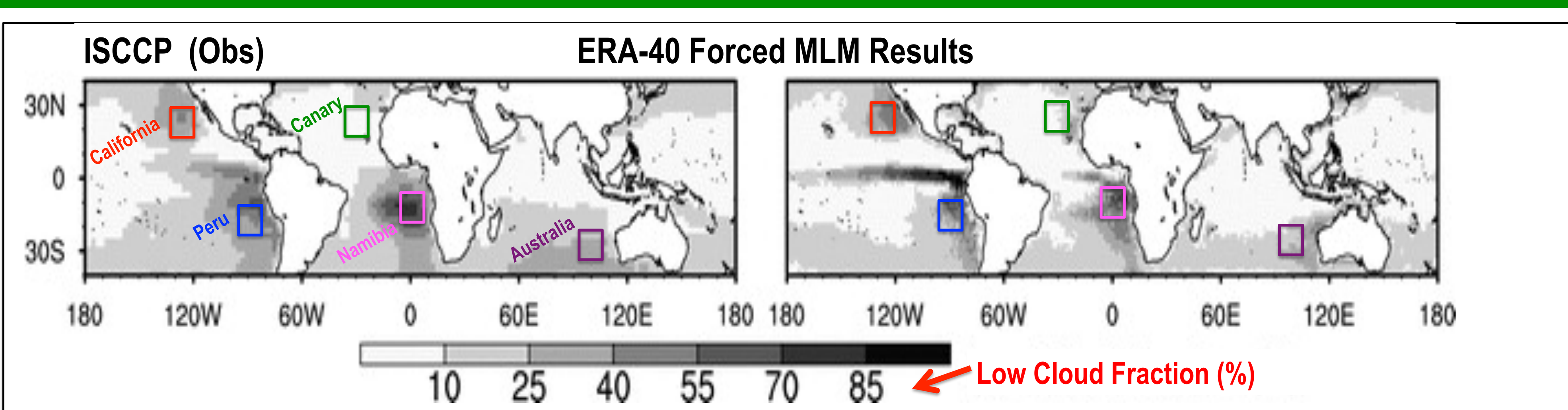

Fig. 2: Observed and ERA-40 reanalysis-forced MLM Sept-Nov. tropical low cloud distribution (adapted from Zhang et al. J. Clim. 2009)

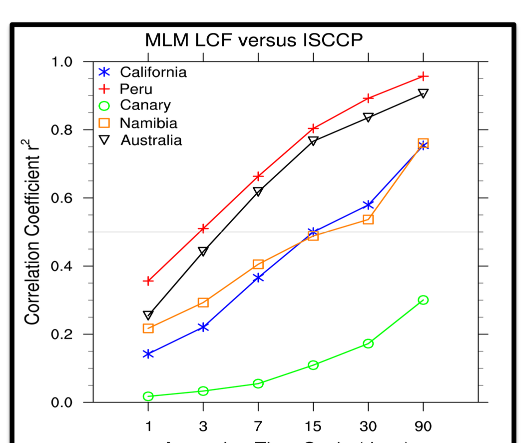

Fig. 3: r^2 between ISCCP and MLM regional-average data when output data (and obs) are averaged as indicated.

- Fig. 2 shows that the MLM reproduces the subtropical stratus areas of Klein & Hartmann (J. Clim. 1993)
- Near-coast & equatorial cloud are overpredicted in Fig. 2 (since sharp ∇SST violates our equilibrium assumption)
- Skill is poor on daily scales but improves rapidly at longer timescales (Fig. 3). Reasons:
  1. high-frequency data is subject to random errors
  2. equilibrium is a less appropriate assumption at short timescales
- Canary region is usually decoupled → unpredictable

Results

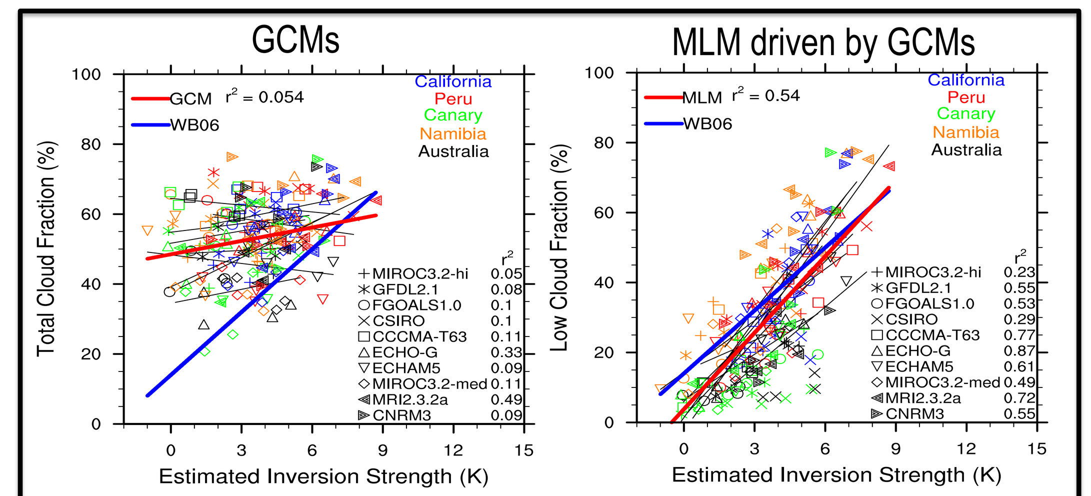

Fig. 4: Current-climate low cloud fraction vs estimated inversion strength (EIS). Each point represents a unique (model, region, season) combination. Thick blue lines = observed slope from Wood & Bretherton (2006), thick red lines are regressions across models and thin red lines are for individual models.

- Fig. 4 shows that CMIP3 models are inadequately sensitive to EIS change
  - This is a problem with *cloud physics* – the MLM responds appropriately when driven by GCM large-scale conditions

In Fig 5 we see:

- MLM runs generally predict *increased* low cloud in the future, GCMs predict *decreased* low cloud
- The MLM does *not* reduce inter-model spread
  - Improving cloud physics is a necessary but not sufficient condition for reducing inter-model spread!

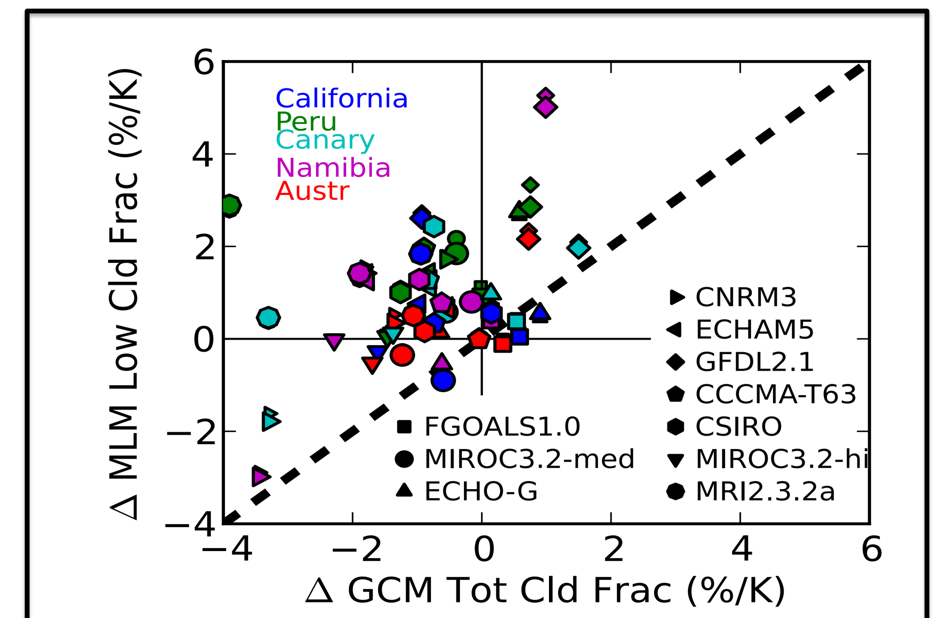

Fig. 5: Low cloud response to climate change as predicted from MLMs and from GCMs stratified by region and model. Direct CO_2 effect was included by reducing cloud-top radiative cooling by 4 W/m². Smaller points show results when this effect was omitted.

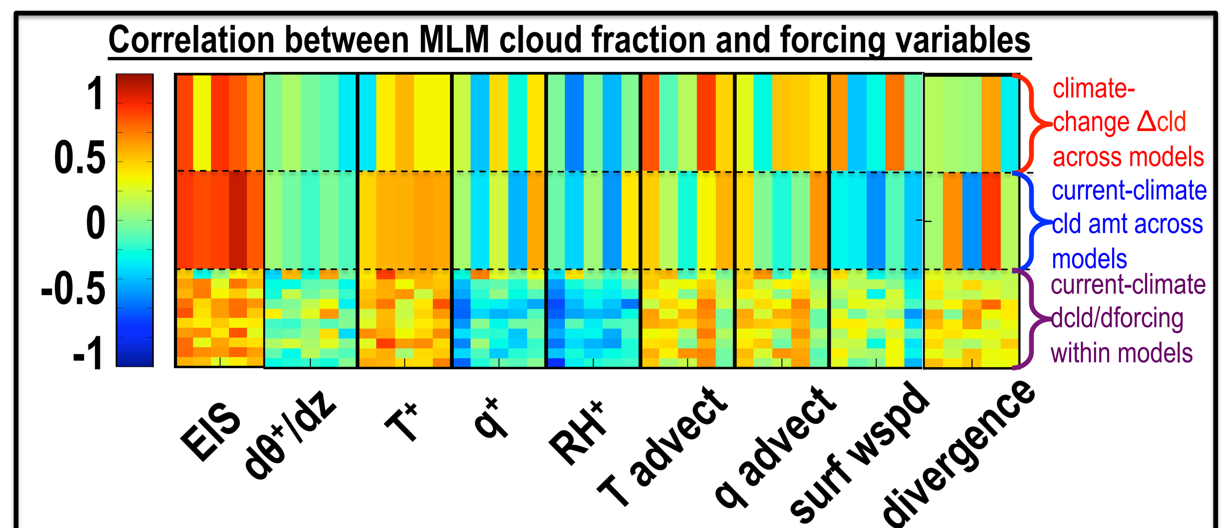

Fig. 6: Correlation between MLM low cloudiness and forcing variables for timescales listed on right. Within each box, correlations are further by region. In the bottom row, correlations are further divided by model.

- EIS is the best predictor of MLM cloud variations in climate projections as well as current climate (Fig. 6)
- MLM cloud increases in the future because of robust GCM EIS increases (Tab. 1)
  - EIS increase comes from increased warm/cold pool ΔSST and enhanced land/ocean T contrast (Fig. 7)

	div (10^{-7} s^{-1})	EIS (K)	$d\theta^+/dz$ (K km^{-1})	SST (K)	T^+ (K)	RH^+ (%)	surf wspd (m s^{-1})
Namibia	**-1.0**	**1.0**	**0.8**	**2.3**	**2.3**	-2.3	**-0.1**
Peru	**-2.0**	**1.1**	**0.8**	**2.2**	**2.3**	-0.6	0.1
California	-0.3	**0.7**	**0.6**	**2.4**	**2.8**	**-1.2**	**-0.2**
Canary	-0.4	**1.1**	**0.7**	**2.3**	**2.8**	**-3.5**	**-0.1**
Australia	**-1.0**	**0.9**	**0.7**	**2.0**	**2.5**	**-2.9**	**-0.1**

Table 1: Climate change signal in large-scale forcings used to drive the MLM. Numbers are in bold where 8/10 models have changes of the same sign.

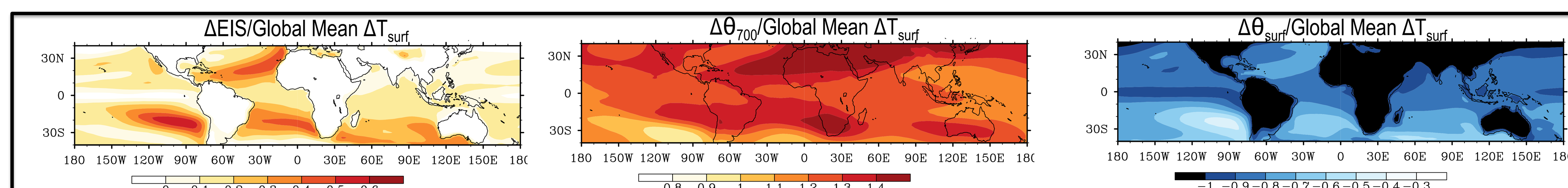

Fig. 7: Pattern of EIS and its components' response to climate change averaged over available CMIP3 + CMIP5 models after each model was normalized by global-mean surface T change. Impact of lapse-rate changes were neglible.

Conclusions

1. The analyzed CMIP3 models displayed poor sensitivity to EIS variations
   – due to cloud physics parameterizations - MLMs driven by these GCMs *did* get the proper sensitivity
2. The MLM did *not* reduce inter-model spread – large variations in ΔEIS across GCMs disperse the MLM predictions, suggesting that improved cloud physics is insufficient to reduce low cloud uncertainty
3. In general, the MLM predicts an increase in low clouds (the opposite response of most GCMs)
   – this increase is due to robust predictions of EIS increase across CMIP3 models. These increases are due to changes in SST patterns as well as future increases in land/ocean temperature contrast

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